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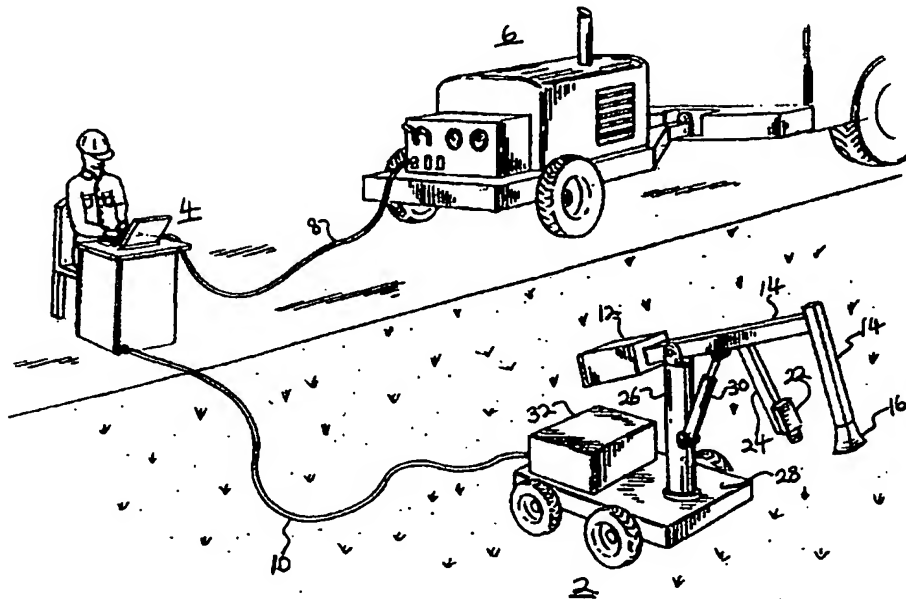
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(54) Title: APPARATUS AND METHOD FOR DETECTING HETEROGENEITIES BY THERMAL IMAGING OF MICROWAVE IRRADIATED TERRAIN



(57) Abstract: An apparatus and method (Fig. 1) are provided for detecting heterogeneities, such as objects and materials, in terrain. A microwave generating system (6), transported on a remote vehicle (2), is used to irradiate terrain at a selected location with microwave energy. An infrared imaging system (22), associated with the microwave generating system, images the thermal responses of the terrain to microwave irradiation, and heterogeneities are detected as areas of different temperature or temperature change within the infrared image. The apparatus and method also use an image processor (4) to help in detecting heterogeneities in terrain, which might include land mines, minerals, ores and other objects and materials of humanitarian and economic interest.

**APPARATUS AND METHOD FOR DETECTING
HETEROGENEITIES BY THERMAL IMAGING
OF MICROWAVE IRRADIATED TERRAIN**

TECHNICAL FIELD

5 The present invention relates to an apparatus for detecting surface and subsurface objects and materials in an area that may be obscured or camouflaged by a background matrix. More specifically, the present invention relates to an apparatus and method for detecting and finding, through infrared imaging and image analysis, objects and materials that are heterogeneities within terrain by their thermal responses to microwave radiation
10 from an active, controlled source of energy such as a microwave generating system.

BACKGROUND ART

Many methods and devices have been developed to locate objects that are hidden, buried, or otherwise obscured within terrain. Underground utility wires, cables, pipes, and potentially valuable items such as coins and lost jewelry are a few examples of obscured
15 objects that are difficult to find. Of particular humanitarian importance, is the need to identify and locate land mines and related ordinance. Inductive, sonic, ground penetrating radar, passive infrared imaging and other methods have been used in a variety of configurations to find objects that are obscured or hidden in or on the ground, camouflaged by natural or man-made means, or difficult to see because of obscuring effects of
20 background clutter.

Ground radar systems are exemplified by U.S. Pat. No. 5,499,029 and U.S. Pat. No. 3,831,173. Such systems transmit radio frequency signals into the ground and rely on the reflection of these signals to locate underground objects. Ground radar systems receive reflected radio frequency signals from the ground, but do not use infrared imaging, to locate
25 underground objects of interest.

U.S. Pat. No. 5,444,241 provides a method for detecting flaws in man-made structures whereby a structure is heated and then scanned with at least two different wavelengths of radiation to correct for surface emissivity and other potential sources of noise and clutter. This patent is specifically directed toward flaw detection in a man-made

structure. No disclosure is made for locating land mines and dangerous ordinance or geologic materials of value that are in the earth environment or terrain.

U. S. Pat. No. 3,713,156 discloses a surface and subsurface detection device where objects that are illuminated with microwave energy reflect the microwave energy back to
5 a focal plane where a microwave to thermal converter converts the reflected microwaves to thermal images. This patent does not disclose direct heating of objects of interest by microwave illumination, but, rather, discloses the reflection of microwave energy back to a liquid crystal-based imaging system, which is itself heated by the reflected, secondary microwave energy to form an image.

10 U. S. Pat. No. 5,209,355 describes a method and apparatus for sorting solids composed of particles whose different dielectric properties determine the amount of energy absorbed by a particular particle. A microwave furnace is used to heat a mixture of materials provided on a conveyor belt, for example, and a temperature detector, such as a pyrodetector, is used to identify particles that constitute impurities of the material. An air
15 jet is directed at the undesired particles to remove them from the material. The technology removes particles from a mixture which has already been collected and processed to the extent that it is provided in a relatively controlled environment and conveyed by a conveyor belt or other conveying means. It is essentially a sorting process and apparatus. No imaging of terrain is performed. Dangerous ordinance and mines by their very nature are
20 not detectable by this technology, because they will explode as soon as they are disturbed. Furthermore, the disclosed apparatus and method could not be used in situ in terrain to identify economically beneficial ores and minerals. Therefore, as disclosed, this invention does not teach the detection of objects and materials in terrain.

It is an object of the invention to provide an apparatus for detecting, locating, and
25 identifying heterogeneities in terrain.

It is another object of the invention to provide an apparatus capable of producing a thermal image of heterogeneities such as objects and materials contained within a background field or matrix, even if these objects and materials are covered by or at least partially buried within the substances or materials of the background field or matrix.

It is a further object of the invention to provide an energy source for directly or indirectly heating terrain at a location, and an infrared imaging system for detecting the thermal response of the material or materials that make up the terrain.

It is yet a further object of the invention to provide a means for heating objects and materials within the field of view of an infrared imaging system so that the infrared imaging system can detect or locate objects and materials within its field of view.

It is still another object of the present invention to provide a remote means for safely locating camouflaged, obscured, buried, hidden, or otherwise difficult to detect objects.

It is yet an additional object of the present invention to provide an infrared imaging system whose output data can be used in data fusion, or otherwise combined, with the data of other sensing and detecting systems to enhance object and material detection remote from the detection system.

The present invention actively irradiates terrain with microwave energy and images the terrain with an infrared imaging system to view temperature responses to the microwave energy of objects and materials in the terrain. Particular objects and materials that make up heterogeneities in the terrain are thus distinguishable from other objects and materials by thermal patterns caused by microwave heating and imaged by the infrared imaging system.

An object or material radiates energy according to its temperature, which is a function of its energy content. The wavelength of the energy radiated from an object or material is dependent on the temperature of the object. For example, an object whose temperature is "white hot," such as the filament of a light bulb, radiates in the visible spectrum. As an object cools, the wavelength of its radiated energy becomes longer (e.g., its color changes from white hot to red) and the object appears darker to the unaided eye. When the filament of an electric stove is at a "medium hot" level or less, it may appear to an observer to be dark (that is, in the spectrum of wavelengths visible to the human eye), but is, in fact, radiating energy in the near infrared (NIR) region or, if cooler, in the middle infrared region (MIR) of the electromagnetic spectrum. Because most objects in the ambient environment are relatively cool compared to light bulb filaments and electric stoves, they radiate electromagnetic energy in the far infrared (FIR) region of the electromagnetic spectrum. Infrared radiation can be detected and, indeed, imaged by infrared imaging systems, which are like television or video cameras except that they operate in a specified

portion or band of the infrared region of the spectrum. Such imaging systems are well known and available from a variety of manufacturers. For example, some "night vision" systems used in law enforcement and by the military operate in a portion of the infrared spectrum. Furthermore, special infrared imaging systems are used in energy audits for
5 detecting "hot spots" on the outside of a house to locate areas of heat loss. In the FIR region, imaging systems such as FLIR (Forward Looking Infrared) systems, can provide high quality imaging of the ambient environment, even in difficult conditions such as haze, smoke, and rain.

It is also known that electromagnetic energy radiating at radio frequencies, including
10 microwave frequencies, can be used to heat objects and materials. This phenomenon has been particularly useful as the operating principle of microwave ovens, which quickly heat foods and other materials. Furthermore, there are numerous industrial uses of radio frequency and microwave frequency energy that include (but are not limited to) curing polymers, pasteurizing, disinfestation, drying, etc. Common frequencies in use for
15 microwave heating are 915 MHz and 2450 MHz. Heating with even lower radio frequency (rf) energy has been considered for, among other uses, extracting hydrocarbons from the ground and remediating sediments containing polluting hydrocarbons. Lower frequency radio waves tend to penetrate farther into the earth than higher frequency radio waves.

Materials are heated by electromagnetic energy by a variety of mechanisms,
20 including dipole rotation, resistive heating, electromagnetic heating and dielectric heating. Depending on their properties, different substances respond to electromagnetic energy by one or more of these mechanisms. Thus, for example, if a conglomerate mixture of heterogeneous materials with different properties is irradiated by microwave energy for a given duration, it is likely that different components of the mixture will, during heating,
25 respond with different rates of temperature change, and, at the end of the irradiation time, have attained different temperatures. Likewise, different components of a conglomerate heterogeneous mixture will cool at different rates.

In addition to the particular mechanism by which a given material component of a mixture is heated, its temperature and rate of temperature change will also be a function
30 of its density, volume, heat capacity, contact with other materials, and other factors. To an observer viewing a conglomerate mixture of materials with an infrared imaging system

before, during, and after the microwave irradiation process, different materials are distinguishable by the different temperatures attained at any point of non-equilibrium during the heating process resulting from their different responses to the radiant microwave energy. Before irradiation, the heterogeneous materials may have attained a state of relative thermal equilibrium within the environment. That is, despite their differential response to electromagnetic (e.g., microwave) heating, convection, and other processes (assuming a relatively constant ambient temperature) will cause the different materials to attain a constant temperature state reflecting an energy balance within the thermal system. When the heterogeneous mixture of materials is irradiated, different materials will respond with different rates of temperature change, and thus appear visually distinguishable either by a human observer or electronically, when viewed with an infrared system. Particular objects and materials (even voids such as cracks or holes) in terrain will stand out as heterogeneities. For the present invention, the term "heterogeneities" is used to mean dissimilar items or parts (i.e., disparities) within terrain. The term "terrain" is meant to include its usual meaning as a tract of land with reference to its natural features, military advantages, etc., and also geologic formations. For the purpose of the present specification, "terrain" need not relate only to level ground, but can include non-level locations such as cliffs, hills, quarries, and mine shafts, and may also include man-made structures associated with the ground or earth such as paths, roads, and other paved and unpaved areas. Therefore, heating terrain by microwave radiation affords a controllable contrast enhancement of heterogeneities in the terrain not available through passive heating due, for example, to solar radiation.

The present invention is used to detect objects and materials and other heterogeneities within a selected area of terrain by heating, with electromagnetic radiation, the terrain and the conglomerate mixture of materials, objects and other heterogeneities comprising the terrain, and imaging the irradiated terrain in the infrared part of the electromagnetic spectrum. Different objects and materials that make up the heterogeneities in the terrain are distinguishable in the image because they respond differently to a given amount of irradiated electromagnetic energy. Objects composed of long-chain polymers (i.e., plastics) may not heat significantly, and thus appear as cool spots compared to the surrounding materials. Objects composed of metals can become very hot when irradiated

by electromagnetic energy because they act as antennas in which relatively large currents are caused to flow. Thus, while certain objects and materials may not be easily apparent in the visible part of the electromagnetic spectrum, they will be more distinguishable in the infrared portion of the electromagnetic spectrum particularly after being irradiated by electromagnetic energy. Man-made objects with distinct features, such as shapes and compositions not typically found in nature, will stand out even if they have been deliberately camouflaged. These objects and materials can be on the surface of the ground, or partially buried, or completely buried beneath the surface of the ground. That is, they can be surface or subsurface objects. When partially or completely buried, objects can still be affected by ground penetrating electromagnetic radiation. Depending on composition, they can appear as cooler or hotter areas in contrast to the medium of the surrounding terrain. Furthermore, when objects such as land mines are purposely set on or in the ground, the surrounding earth is disturbed and thus often distinguishable, with the present invention, as disparities from undisturbed earth. This is particularly true of roads, paths and well traveled areas where land mines have been laid. These areas are regularly subjected to anisotropic forces of moving vehicles and people, which form ground patterns (e.g., cracks, pebble distribution, packed soil) that are disturbed when land mines are laid.

In the present invention, the irradiating period of electromagnetic energy can be continuous or pulsed. Pulses can be of a uniform duty cycle and/or repetition frequency, or of a variable duty cycle and/or repetition frequency. Furthermore, the infrared imaging system of the present invention can sample infrared light emitted from the irradiated ground area either continuously or in a switched or gated mode. In the switched or gated mode, infrared light is sampled only at preselected times of preselected durations. Gating can be synchronous with one or more of the electromagnetic irradiating heating pulses. For example, the gating period of the infrared system can be preselected to be completely synchronous, or in phase, with the heating pulse period, or it can be preselected from a range of intermediate phases ending with a completely asynchronous period wherein the infrared image is never sampled during the "on" time of the electromagnetic heating pulse. Gating is a sampling process that can be done with a mechanical shutter associated with the infrared camera, or electronically (e.g., by switching circuitry that selects images at different times).

In the present invention, the irradiating electromagnetic energy can be polarized by using a polarizing antenna or applicator, as is known in the art. The angle of polarization can be altered by changing the orientation of the antenna or applicator (e.g., by rotation) or by using two or more antennas or applicators with fixed but different polarization angles.

5 Similarly, in this invention, infrared polarizing optics can be used with the infrared imaging system to provide additional resolution and enhancement. For example, different materials, depending on their composition and orientation, can, when heated, produce infrared light that is preferentially polarized. By viewing such light with an adjustable angle
10 infrared polarizer, these materials are more easily distinguishable from non-polarizing, potentially obscuring materials in the field of view. An infrared polarizer can be placed in front of an infrared imaging camera to provide infrared polarized light.

Thus, with the present invention it is possible to view the differential response of objects and materials to electromagnetic heating. For example, infrared images can be produced during or shortly after the heating process, and also during the cooling process.
15 Furthermore, measurement of the temperature rate of change of specific portions of sequential images provides more information than is available from a single image produced at a specific time. Such information can be subjected to data processing and image processing techniques to provide enhanced images and data that facilitate improved analysis and decision making. The invention enhances the ability to distinguish between different
20 objects and materials, and thus, heterogeneities, within terrain.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a general view illustrating the present invention and its use in the field.

Fig. 2 is a block diagram of a preferred embodiment of the apparatus in accordance with this invention.

25 Fig. 3 is a general view illustrating an alternative embodiment of the present invention including a parabolic reflector for applying microwave energy.

Fig. 4 is a general view illustrating an alternative embodiment of the present invention including a parabolic cylinder for applying microwave energy.

BEST MODE FOR CARRYING OUT THE INVENTION

An important use of the apparatus and method of the present invention is to detect heterogeneities in the terrain such as land mines and other dangerous munitions or objects that may be completely or partially hidden or obscured within the geophysical environment.

- 5 For purposes of illustration, the apparatus of the present invention is shown in Fig. 1 as typically deployed. Remote vehicle 2, which can function autonomously or under an operator's control, is an instrument support and transport platform for the detection system of the present invention. As shown in Fig. 1, remote vehicle 2 is controlled by an operator at command station 4, which is located in a safe area remote from the survey location.
- 10 Electric power generator 6 provides electric power through electric power cable 8 to command station 4, and, as shown, via the command station 4 to remote vehicle 2. Signal and control cable 10, which connects command station 4 with remote vehicle 2, supplies power to remote vehicle 2 and provides command, control, and data signal lines between command station 4 and remote vehicle 2. Remote vehicle 2 is a movable instrument
- 15 platform for supporting, transporting, and pointing a microwave energy source at terrain where it can be used in combination with an infrared imaging system to identify, detect, and locate surface and subsurface details comprising heterogeneities in the terrain. For example, the present invention may be used to prospect for economically valuable materials such as metals, minerals, and ores, or to discover gemstones within rock veins or voids.
- 20 Alternatively, it may be used to detect and locate dangerous objects such as land mines or unexploded ordinance on the surface or under the surface of the earth. The above uses are described for exemplary purposes only, and are not meant to limit in any way the scope of the present invention.

- Command station 4 will usually, but not necessarily, be manned and operated at a
- 25 relatively safe and secure location a distance from remote vehicle 2, which is designed for use in a rugged environment and is constructed of strong, impact-resistant materials selected from those known in the art, both to maintain the vehicle's structural integrity and to protect and enclose, as much as possible, any sensitive, delicate instruments. In the preferred embodiment, as shown in Fig. 1, command station 4 is connected to, and in
- 30 electrical communication with, remote vehicle 2 through the signal and control cable 10, which also provides power to remote vehicle 2. Signal and control cable 10 provides power

and control signals for driving remote vehicle 2 as well as the mechanical (e.g., instrument positioning and targeting) and electronic operations of the microwave and infrared instruments on the vehicle. Furthermore, signal and control cable 10 also carries data signals from remote vehicle 2 and its instruments, conveying them to command station 4.

- 5 These data include image signals (which can typically be in a video format), remote vehicle 2 location information, pedestal angle information, and ancillary data signals such as instrument status bits.

As is clear in Fig. 1, to provide an image of the thermal effects microwave energy application, the infrared imaging camera 22, mounted on camera support member 24, and
10 microwave applicator 16 are aimed at the same general terrain in the environment. Thus, at least a portion of the field of view of the infrared imaging camera includes a portion of the area or location that receives microwave energy from the microwave applicator 16. Microwave applicator 16, microwave energy source 12, microwave waveguide 14, infrared imaging camera 22, camera support member 24, are movably mounted on pedestal 26.
15 Pedestal 26, can rotate in a plane parallel to the top surface of instrument platform 28. Linear actuator 30 is used controllably to vary the angle of the infrared imaging camera 22 and microwave applicator 16 in a plane normal to instrument platform 28, thus varying the optical and microwave boresight angle of incidence with respect to the target area. Microwave energy can be applied to terrain from a distance (i.e., microwave applicator 16
20 radiates microwave energy at the terrain without touching the terrain) or directly by injecting microwave energy directly into the terrain (i.e., microwave applicator 16 contacts the terrain).

Enclosure 32 on instrument platform 28 preferably contains an electric motor based vehicle drive system, which includes the necessary electromechanical and mechanical
25 assemblies known in the art for driving and steering remote vehicle 2, the power for which is received from electric power generator 6, via signal and control cable 10. Enclosure 32 also contains electronics for interfacing and communicating with command station 4 and processing the command, control, and data signals that are conveyed through signal and control cable 10, which in addition to power, provides a bidirectional data link between
30 remote vehicle 2 and command station 4.

In autonomous operation, remote vehicle 2 operation is controlled by an autopilot, with or without a tether to command station 4 through signal control cable 10 as shown in Fig. 1. Remote vehicle 2 can also be equipped with a wireless link for video and data signals either in place of or in addition to signal control cable 10. When operating without
5 signal control cable 10, remote vehicle 2 carries its own power source.

Remote vehicle 2 is equipped with navigation means such as are known in the art. For example, the navigation means can consist of a GPS (Global Positioning Satellite) system, or it can be as simple as using distance and direction data that are correlated with way points on a map.

10 Mechanical and electronic interfaces for accommodating additional detection technologies are provided by the present invention. Data from diverse detection systems can be combined and processed synergistically and analyzed to great advantage by sensor fusion techniques well known in the art. An exemplary list of such additional detection technologies, but which is not meant to be limiting in any way, includes metal detection
15 systems, ground penetrating radar, explosives detectors, millimeter wave emission detectors, and others.

Additional options can be used with the present invention to enhance its operational capabilities. The following are provided for exemplary purposes only and are not intended to limit the scope of the present invention. A fan or other air blower can be mounted on
20 instrument platform 28, and used for mechanically displacing vegetation, soil, rocks, and other debris. Moving air from a fan or blower can also be used to cool a target area by convection, thus providing an additional temperature varying mode of operation of the present invention. Additional mechanical means for disturbing a target location in the earth environment include use of a projectile propelling means or an extensible actuator.

25 A target location can be disturbed non-mechanically through the use of a controllably pointable high power laser mounted on instrument platform 28 to heat, and even burn away, organic debris that may be obscuring an area of interest in a target location. Such a laser can also be a source of highly localized heat for use with the infrared imaging camera 22 to enhance the resolution capability of the present invention.

30 Another exemplary option for use with the present invention is a device for marking or flagging (e.g., using paint, chalk, darts, beacon, laser, etc.) a specific location of interest.

For example, paint or chalk can be sprayed from an optional sprayer mounted on instrument platform 28 to highlight a particular area of the ground that might, for example, be the specific location of an antipersonnel mine.

It is also anticipated that a plurality of instrumented remotely piloted vehicles can
5 be used concurrently and in concert under the control of command station 4. Information and data from each of a plurality of instrumented remotely piloted vehicles can be analyzed and monitored separately, or combined electronically to provide a composite view of the target location using data fusion and other techniques known in the art.

Fig. 2 is a block diagram of the preferred embodiment of the present invention. As
10 shown, the system is partitioned into three sections corresponding to remote vehicle 102, command station 104, and power source 106. Particularly in remote or primitive areas, power source 106 is usually a transportable electric generator typically based on an internal combustion engine and capable of generating sufficient electric power to operate both remote vehicle 102 and command station 104. Such generators are well known in the art
15 and available commercially. In other circumstances of use, such as in an established commercial mining operation, power source 106 may be a stationary industrial electric generator, or even the electric power grid available from a local electric utility.

Power source 106 provides electric power via electric power cable 108 to command station 104 through electric power cable branch 108a and to remote vehicle 102 through
20 electric power cable branch 108b which, as shown in Fig. 2, is bundled with signal and control cable 110. Command station 104 controls system function, processes, analyzes, and displays image data, processes data from auxiliary sensors, and commands optional actuators. Functional blocks in command station 104 are computer 140, image processor 142, image memory 144, image display 146, and sensor fusion processor 148.
25 The functional blocks of the remote vehicle 102, include vehicle drive and control 150, microwave energy source 152, microwave conduction means 154, microwave applicator 156, pedestal control 158, infrared imaging camera 160, options adapter 162, and auxiliary detection systems adapter 164.

The computer 140 of command station 104 performs systems control, systems
30 integration, and data analysis. Computer 140 typically includes a computer monitor, a keyboard, a mouse, and internal and external peripherals such as printer, disk drives, and

other mass storage devices known in the art. Computer 140 is integrated within the command station 104 with the other functional blocks through data and address bus 170, and through signal lines 172, which provide enable, strobe, clock, and other control signals. Computer 140 transmits signals to and receives signals from remote vehicle 102, via serial data lines 110a, which are part of signal and control cable 110. Data transmission through serial data lines 110a is preferably via a fast, bidirectional serial link, with a modem connected to computer 140 communicating with a modem connected to remote vehicle 102. Although parallel data communications can be performed effectively between two systems remote from each other, because serial data communications cables need fewer signal lines, the weight, cost, and complexity of signal and control cable 110 are minimized using a serial configuration. Video signal lines 110b, also part of signal and control cable 110, convey video signals from the infrared imaging camera 160 on remote vehicle 102 to image processor 142 at command station 104. Depending on the output of infrared imaging camera 160, video signal lines 110b can carry either digital or analog video signals.

The image processing system of the command station 104, includes image processor 142, image memory 144, and image display 146, which can be an additional display separate from the computer monitor or functionally part of the computer monitor as a software generated "window." The image processing system can record, store, and process images from one or more infrared cameras. It can also combine different images from the same camera or from different cameras. These images can be concurrent or spaced apart in time. A particular image can be compared to earlier stored images, which can be single images or composites produced from a selected combination of a plurality of previously stored images. When images are successively stored, they can be processed (e.g., algebraically added or subtracted or "differenced") to provide temperature rate of change information, which is valuable in materials analysis and identification. Multiple images can be from the same camera or from different cameras that are spatially separated.

The image processor 142 is designed to facilitate pattern recognition to help identify objects and materials of interest in terrain. For example, it can produce "pseudo-color" images where different colors are used to designate different temperature zones. This enhances the ability of the observer to differentiate gray scale gradients. Recorded images of known objects can be stored in image memory 144 and used by the image processor 142

as templates against which shapes or other features of heterogeneities in terrain, imaged with infrared imaging camera 160, can be compared or correlated. Such a comparison can also be made with single recorded images or stored images that are composites of a plurality of images.

5 When multiple cameras are used, they need not all be sensitive to the same wavelengths. For example, an image from an infrared camera can be combined with an image from a visible light camera to provide enhanced images through superposition, feature addition and subtraction, correlation, and other known image processing techniques. U.S. Pat. No. 5,555,324, incorporated herein by reference, discloses ways to produce
10 synthetic images by fusing signals representing different views of the same scene.

 Sensor fusion processor 148 is provided in command station 104 for use when additional sensing systems are used in concert with the present invention. Sensor fusion processor 148 can receive and process both image data and non-image data, depending on what additional sensing systems are used. Additional sensing systems can be mounted
15 directly on remote vehicle 102, as auxiliary systems, or they can be sensing systems independent of and separate from the remote vehicle 102. Furthermore, data processed in sensor fusion processor 148 need not necessarily be produced concurrently with the image data of the current invention. Previously recorded data or data extracted from image memory, computer memory, or other data storage means can also be used by sensor fusion
20 processor 148.

 Remote vehicle 102 provides a moveable instrument platform that can be operated under the control of an operator nearby or at a remote location, or autonomously according to a programmable autopilot. A special benefit of the remote vehicle is that it can be used in a potentially dangerous location by an operator at a safer location. This is particularly
25 beneficial when the system is used for locating land mines, hidden munitions, and performing other dangerous detection tasks. As shown in Fig. 2, remote vehicle 102 is driven and controlled by vehicle drive and control 150, which receives power through electric power cable branch 108b and command and control signals via serial data lines 110a, which are part of signal and control cable 110. Remote vehicle 102 serves as
30 a platform for microwave energy source 152 and infrared imaging camera 160. Vehicle control lines 174 and vehicle power lines 176 provide control signals and power

respectively from vehicle drive and control 150 to all the functional subassemblies of the remote vehicle 102 shown in Fig. 2.

Microwave energy source 152 provides microwave energy to the microwave applicator 156 through microwave conduction means 154, which can be a waveguide or coaxial cable. Infrared imaging camera 160 provides thermal images most usually in a video format, the signals of which are transmitted through video signal lines 110b, which are part of signal and control cable 110, to image processor 142 located at command station 104. Both the microwave applicator 156 and the infrared imaging camera 160, mounted on the same or separate pedestals, can be steered and aimed under the command of pedestal control 158. Options adapter 162 allows for the mounting and control of optional devices that can be used in concert with the present invention. Examples of optional devices are a fan (e.g., for moving vegetation at a location), a laser for additional heating, and a marking device capable of marking specific locations in terrain with chalk, paint, or other easily noticeable substances. Auxiliary detection systems adapter 164 provides an electronic and mechanical connection to additional detection systems that can be used in concert with the present invention.

The microwave energy source 152 is a microwave generator that can be chosen from a variety of microwave generators currently commercially available or it can be custom designed according to desired specifications. For example, Cober Electronics of Norwalk, Connecticut has microwave generators available at 915 MHz and 2450 MHz, frequencies most commonly used in industrial heating applications. Microwave generators typically include power supply, controls, and magnetron integrated together. Other companies currently marketing microwave power generators include: CPI-Microwave Power Products, Palo Alto, CA, Thermex-Thermatron, Inc., Hauppauge, NY, Ted Pella, Inc., Redding, CA, and others. Microwave generators and components (i.e., waveguides, feed horns, antennas, etc.) are available from these and other manufacturers, and can be easily adapted by someone with ordinary skill in the art for use with the present invention. Indeed, at its simplest and most economical, the microwave generator can even be implemented using the low cost components and assemblies of consumer magnetron based microwave ovens.

It is contemplated that a single wavelength or a plurality of wavelengths can be used to irradiate a section of terrain. Simplicity is preserved when generating and radiating only

a single wavelength. However, generating multiple wavelengths of microwave energy either concurrently or sequentially yields thermal responses that are richer in spectral information regarding component materials in the area of interest. That is, a microwave/thermal spectral analysis can be performed by irradiating the environment with energy from a preset range of microwave frequencies and analyzing the thermal response of the components in the environment. Depending on composition, particular materials may have unique and specific thermal responses to microwave excitation of any particular wavelength.

Microwave generators based on traveling wave tubes can vary or "sweep" the generated microwave frequency, thus generating multiple wavelengths for irradiation. Lambda Technologies of Raleigh, NC, has developed traveling-wave tube microwave generators of this kind.

Infrared imaging camera 160, preferably operates in the far infrared wavelength band to produce images in the temperature range typical of the ambient environment. Ideally, the infrared imaging camera 160 should be sensitive to small temperature differences, both between different pixels representing adjacent image features, or of a single pixel as it responds to thermal changes over time. There are infrared cameras currently commercially available that are capable of resolving temperature differences of less than 0.2°C. For example, the Argus Falcon™ system available from Raytheon Systems Company, Goleta, CA, operates in the 3 to 5 micron band, with a temperature sensitivity of better than 0.02°C. The system is designed to operate in an ambient temperature range of 0°C to 60°C. The MilCAM-XP available from FLIR Systems, Inc. Portland, OR, also operates in the 3 to 5 micron infrared band. It has a noise equivalent temperature of 0.025°C measured at 23°C ambient temperature, and has an operating range of -20°C to +55°C. Other far infrared imaging systems with different operating bandwidths (e.g., 7.5 to 13 microns), different sensitivities and other specifications are currently available from these and other manufacturers.

Fig. 3 illustrates the present invention used in a geological application. In this alternative preferred embodiment, the system is shown irradiating terrain comprising an embankment with microwave energy and producing an infrared image to determine resulting temperature differences of surface and subsurface features of the embankment.

Temperature differences will result from the microwave heating processes already discussed above and will be different from the temperature profile of surface and subsurface features that is due to passive heating from the environment (i.e., solar heating, wind cooling, etc.). When dynamic temperature changes (e.g., rate of temperature change) of certain features
5 are caused by continuous or repeated pulse microwave irradiation, the temperature change of these features over time, as measured and indicated by the infrared image, becomes a useful diagnostic of the irradiated environment. Thus, when a given material comprising a heterogeneity contained within a particular background matrix of terrain is irradiated at a preselected microwave energy level, a specific signature response will occur, manifested
10 by the rate of temperature change observed with the infrared imaging system. The rate at which the temperature of the given material changes may be different from the rate at which the temperature of the surrounding matrix changes. Through image processing techniques (e.g., image transforms, integration, correlation), the image contrast between the given material feature and the background matrix can be enhanced.

15 In Fig. 3, remote vehicle 202, facing the embankment, communicates with a command station (not shown) and receives power via signal and control cable 210. Remote vehicle 202, in this alternative preferred embodiment, is shown supporting a microwave energy source 212, microwave conduction means 214, microwave applicator 216, and parabolic reflector 218, all mounted on support boom 220 which, in turn, is hinged
20 supported on pedestal 226. The angle between support boom 220 and pedestal 226 is controllably varied by linear actuator 230. Within enclosure 232 are contained the remote vehicle 202 drive and control apparatus and other power and instrumentation assemblies discussed herein above as with regard to Fig. 2. Remote vehicle 202, through pedestal 226 and support boom 220, also supports infrared imaging camera 222, which is mounted on
25 camera support member 224. As shown, infrared imaging camera 222 can be positioned and aimed independently of the microwave irradiating structure, thus allowing images to be taken from a range of angles and directions that may be different from the microwave boresight angle and direction. This can be beneficial for inspecting shadowed areas and, also, for producing composite images constructed from a plurality of individual images.
30 Such composite pictures can contain more image information than any single image.

Fig. 4 illustrates another alternative preferred embodiment. In this configuration, remote vehicle 302 has two infrared cameras 322a and 322b mounted on opposing ends of camera support member 324 to provide binocular imaging. The two images produced by both cameras can provide distance information and enhance the system's ability to "see around" obstacles that may be obscuring an area of interest. More than two cameras can also be used if desired. Additionally, it is contemplated that a plurality of microwave radiation sources can be used in concert, each irradiating a particular area of interest from a different position and angle. This would provide microwave radiation from multiple directions, ensuring a more effective coverage of the area of interest to be irradiated.

10 In Fig. 4, support boom 320, is hingedly connected to pedestal 326, which is mounted on platform 328 of remote vehicle 302. The angle between support boom 320 and pedestal 326 is controllably varied for aiming purposes by linear actuator 330. Microwave energy source 312, mounted on support boom 320, provides microwave energy of a presettable wavelength and power to microwave applicator 316 (shown as a feed horn)
15 through microwave conduction means 314 (shown as a waveguide). Reflector 318 receives microwave energy from microwave applicator 316 and directs the microwave energy to the area to be irradiated. Infrared cameras 322a and 322b mounted on camera support member 324 are independently controllable and pointable. Within enclosure 332 are contained the remote vehicle 302 drive and control apparatus and other power and
20 instrumentation assemblies discussed herein above as with regard to Fig. 2.

The infrared camera of the present invention need not necessarily be mounted on the remote vehicle as has been the case in the embodiments discussed above. Indeed, with suitable magnifying infrared optics, the camera can be mounted and operated at a location a safe distance away from the remotely piloted vehicle. As the remote vehicle transports
25 the microwave equipment so that terrain is irradiated with microwave energy, the infrared camera can be pointed at the irradiated terrain for imaging. This has the advantage of preserving the relatively delicate and expensive infrared optics and camera in the event that damage is sustained by the remotely piloted vehicle.

Microwaves are advantageous for heating purposes in the present invention because
30 they are controllable, can penetrate materials to a certain extent, and can be propagated

from distance. However, other heating methods can also be used including radio frequency energy applied to the terrain, heat from radiant heaters, and radiation from heat lamps.

The invention described is not intended to be limited to the embodiments disclosed but includes modifications made within the true spirit and scope of the invention.

CLAIMS

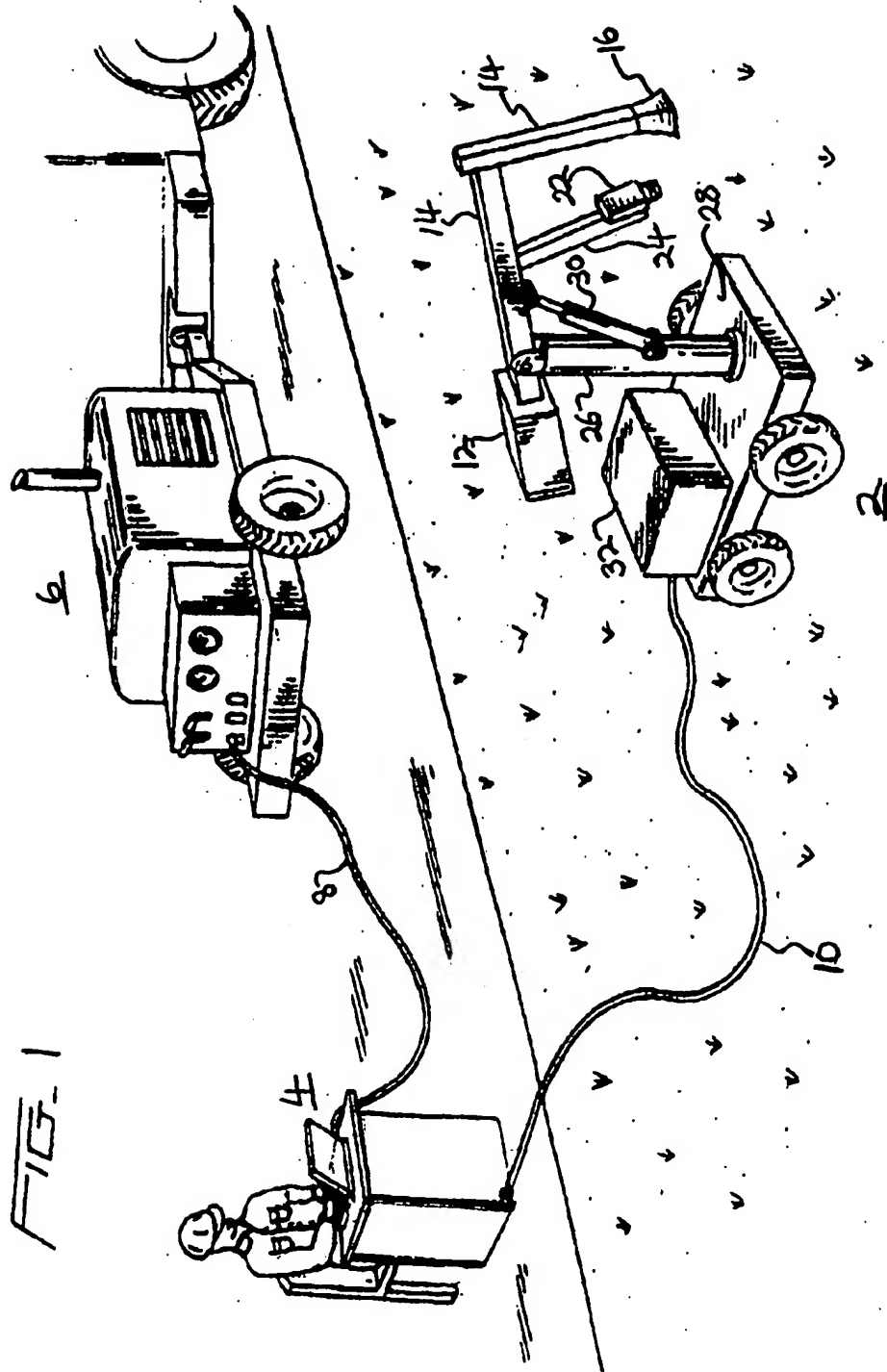
1. An apparatus for imaging heterogeneities in terrain, comprising:
 - (a) a microwave energy source;
 - (b) a portable microwave applicator coupled to said microwave energy source
- 5 for directionally applying microwave energy to said terrain to alter heat energy of said terrain;
 - (c) an infrared imaging means positioned to produce an image of said terrain, said image representing heat distribution of said terrain resulting from applied microwave energy.
- 10 2. The apparatus recited in claim 1 further comprising:

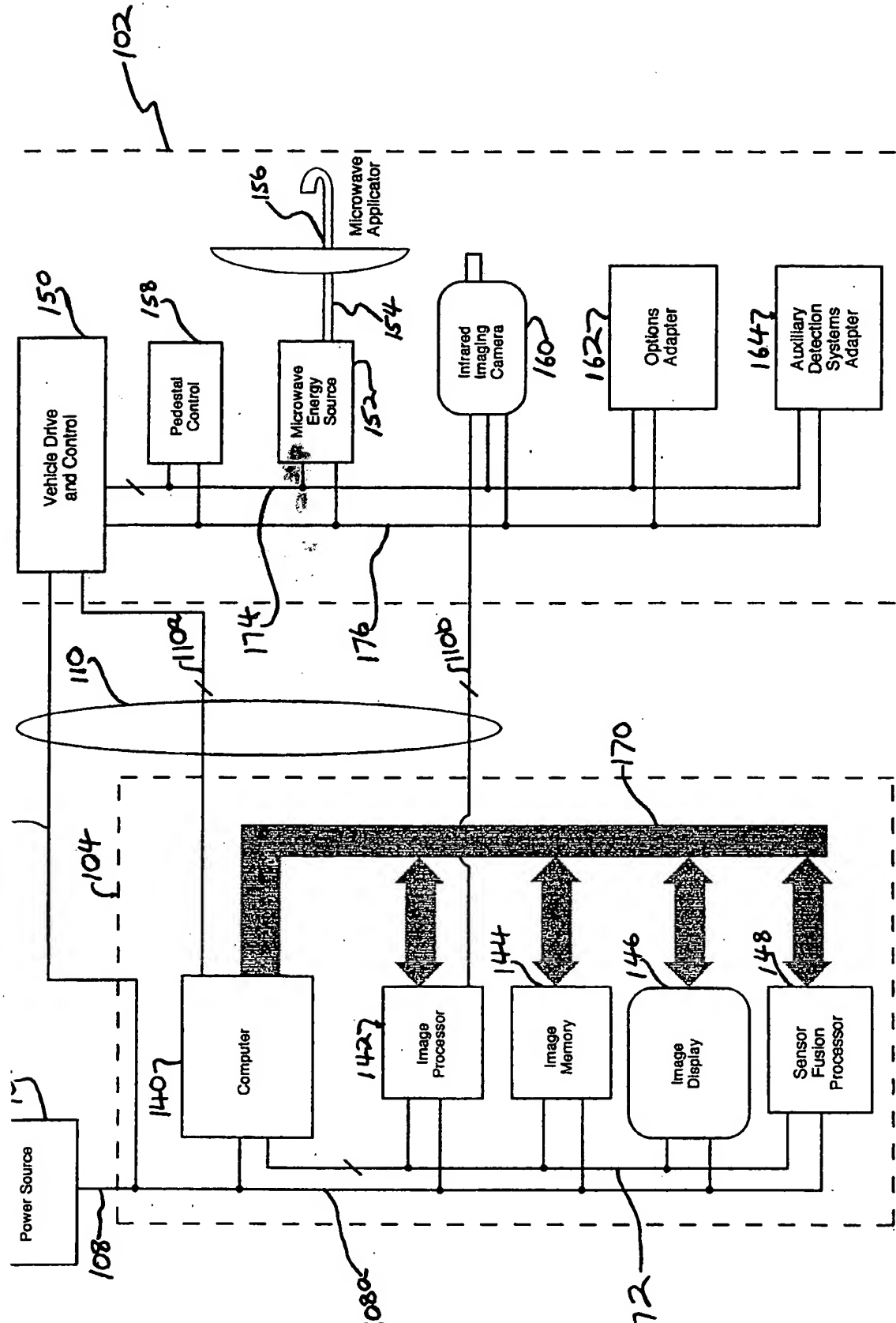
a support means for pointing said microwave applicator, said support means carried on a controllable movable platform so that the position of said microwave applicator with respect to said terrain can be altered.
3. The apparatus recited in claim 2 wherein said support means on said controllable
- 15 movable platform also provides support for said infrared imaging means.
4. The apparatus recited in claim 1 further comprising:

image processing means for receiving and processing said image of said location, to provide a viewable representation of heterogeneities at said location.
5. The apparatus recited in claim 4 wherein said image processing means further
- 20 comprises an image memory for storing image data of at least a first image so that a second image can be compared with said first image.

6. An apparatus for detecting heterogeneities in terrain, comprising:
- (a) a microwave generator;
 - (b) a movable microwave applicator connected to said microwave generator by a microwave conduction means, said microwave applicator receiving microwave energy
5 from said microwave generator through said microwave conduction means, said microwave applicator directionally transmitting said microwave energy at said location of interest;
 - (c) an infrared imaging camera movably mounted to produce signals representing an image of thermal distribution within said location of interest;
 - (d) means for processing said signals to provide image information indicative
10 of the heterogeneities in said terrain.
7. The apparatus of claim 6 wherein said microwave energy generator has a switching means for providing multiple, successive pulses of microwave energy, said microwave energy having a preselected pulse width and frequency.
8. The apparatus of claim 7 wherein said microwave energy generator is controllably
15 tunable to provide a plurality of selectable microwave energy frequencies.
9. The apparatus of claim 6 wherein said microwave applicator is disposed to provide microwave radiation having a preselected polarization.
10. The apparatus of claim 6 wherein said imaging system further comprises an image processor for transforming and comparing selected combinations of previously stored
20 images selected from a series of thermal images.
11. The apparatus of claim 10 wherein said image processor further provides means for producing a composite image representing the difference between signals representing an image of thermal distribution within a first image and signals representing an image of thermal distribution within a second image, said second image derived from at least one of
25 previously stored images, whereby a plurality of sequential composite images provides an indication of the rate of temperature change of items within said location of interest.

12. The apparatus of claim 6 wherein said infrared imaging camera receives infrared radiation through an infrared polarizer.
13. A method for finding materials of interest in terrain within a field of view,
(a) heating said terrain by directionally radiating microwave energy at said
5 terrain;
(b) imaging infrared light from said terrain with an infrared imaging system to provide an image indicative of heat distribution within said terrain;
(c) analyzing said image indicative of said heat distribution for indications of materials of interest.
- 10 14. The method of claim 13 further comprising the step of directionally radiating said microwave energy as multiple, successive pulses having a preselected pulse width and frequency.
15. The method of claim 13 further comprising the step of radiating said microwave energy at a plurality of preselected frequencies.
- 15 16. The method of claim 13 further comprising the step of preselecting the polarity of said microwave energy.
17. The method of claim 13 further comprising the step of comparing said image to selected combinations of previously stored images from a series of thermal images.
18. The method of claim 17 further comprising the step of combining said image with
20 a second image derived from at least one of said previously stored images to produce a composite image representing the difference between said image and said second image thereby determining the rate of temperature within said terrain.
19. The method of claim 13 further comprising the step of polarizing said infrared light before imaging by said infrared imaging system.





FILE 2

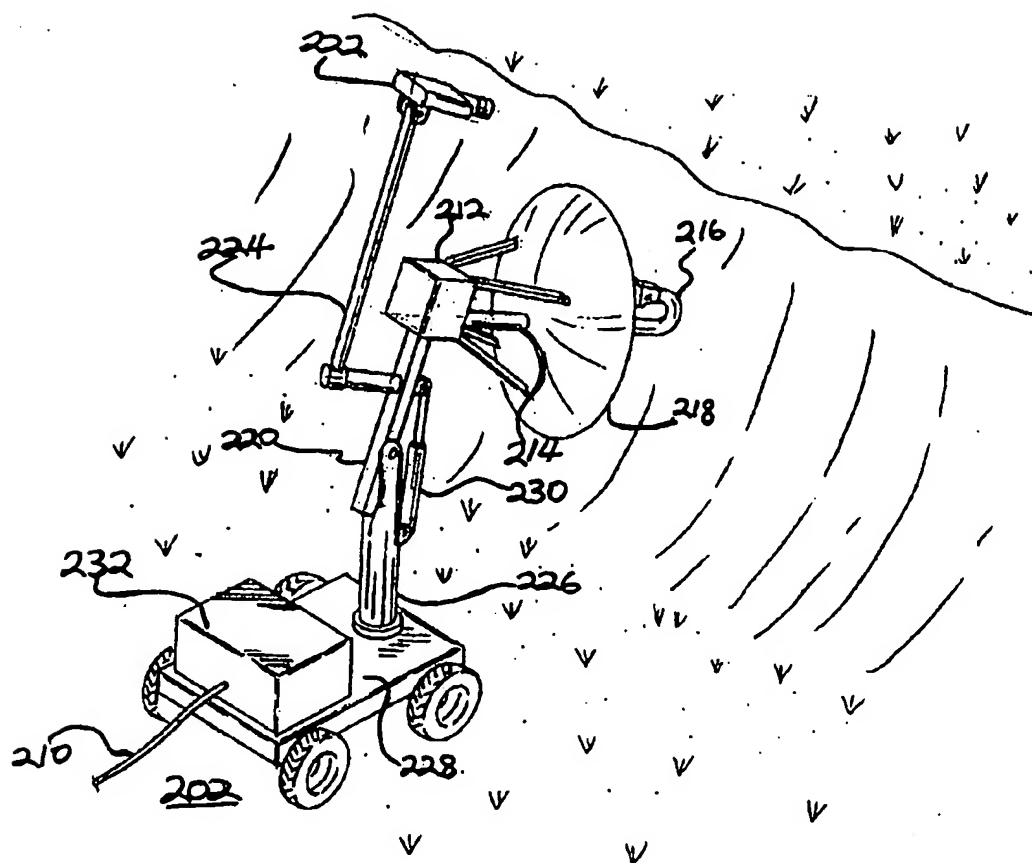


FIG. 3

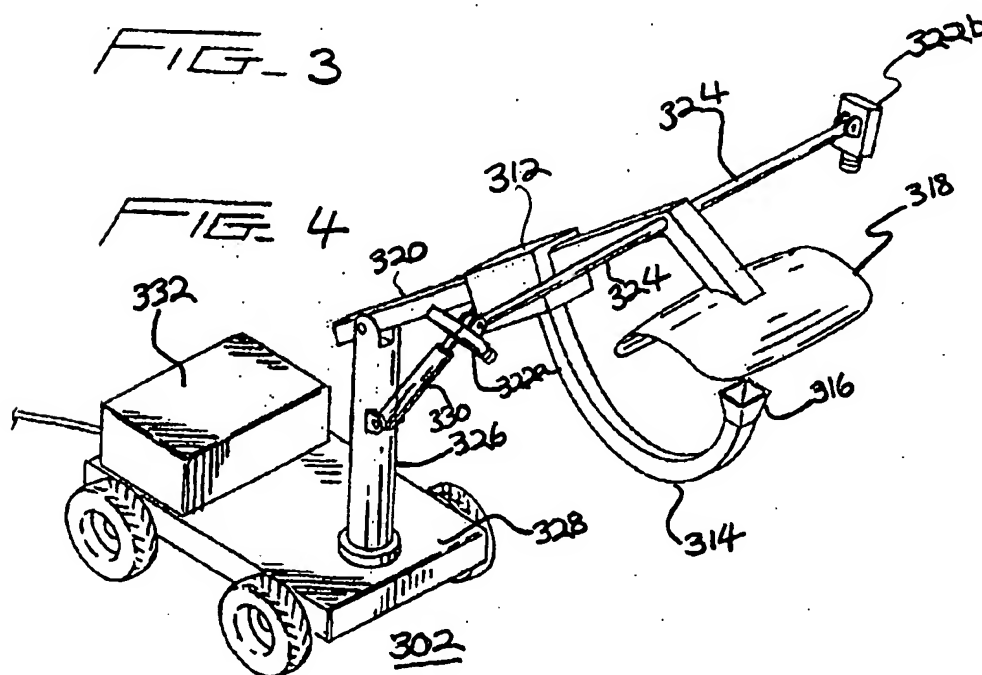


FIG. 4